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For

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The primary purpose of the following discussion is two-fold. One is to present a critical analysis of present and projected power-conditioning capabilities in view of anticipated needs of the National Space Power Program. The other is to serve as a forum by which attention is drawn to those facets of the evolving power-conditioning technology where greater stimulus needs to be applied in order to keep pace with advancements and changing requirements in other areas. The present discussion is not intended as a technical review of the vast number of components and wide variety of circuits in use today. Emphasis instead has been placed on certain underlying principles and on several key ingredients which, to date, have been and apparently will continue to be rather true gauges of the rate of progress attainable in the area of power conditioning.

Continuing ability to adequately accomplish the three power-conditioning functions of inversion, conversion, and regulation assures electrical compatibility between energy sources and spacecraft instrumentation and equipment loads even though the source and loads are conceived and developed independently of one another. Such a capability enables source and load characteristics to be optimized independently and enables the fruits of a great many research programs to be used almost immediately without the cost and delay which might be involved if, for example, it were necessary to re-design an entire payload system around the new characteristics of an improved energy source. Sight should not be lost, however, of the fact that power conditioning within a spacecraft is clearly a function which should be developed and evaluated from the overall-system perspective where source, power conditioning, and load requirements are simultaneously considered.

Power conditioning for spacecraft electrical systems has from necessity been a rapidly evolving technology. Documentation of new developments in the open literature and in technical reports to the government has been quite rapid and complete. Since much of this technical information has, in fact, appeared in government reports rather than in professional journals, two especially valuable sources of information are the abstracting and publication services of the Defense Documentation Center and NASA's Office of Scientific and Technical Information.

Two observations are of such particular significance in an examination of progress to date in the area of power conditioning that they bear stating before entering into a more detailed analysis. They are:

(1) It is, fundamentally, the introduction of new and improved switching elements that opens the door to increased power-conditioning capabilities. That is, the switching element is the limiting factor in the last analysis, and sets limits on size/weight, current, voltage, and power capabilities which can be approached through sophisticated design, but never exceeded. Moreover, the characteristics of the switching element enter directly and indirectly into the system reliability considerations.

(2) Perhaps the most lagging aspect of power-conditioning technology at present is that of reliability. By this is meant the failure to consistently achieve in operational power-conditioning systems a reliability that approaches what one might anticipate from consideration of the reliability of the component devices themselves.

Objectives Of Power Conditioning

The fundamental purpose of power conditioning is to provide by external means the necessary compatibility between energy-source characteristics and load requirements when and if reasons exist which preclude the achievement of this compatibility through more direct design approaches, such as, for example, by modifying or controlling the source characteristics or load requirements. These reasons often include not only fundamental electrical considerations, such as the requirement to operate a-c equipment in a spacecraft whose primary source of energy provides direct current, but also such other considerations as weight/size, efficiency, cost, and protection. For example, it is often a great deal more efficient and economical to design electronic equipment for operation from a well regulated voltage than from a widely variable voltage.

It cannot be emphasized too strongly that power conditioning is fundamentally a "systems" concept. Any given system, should be planned and all decisions made with a full recognition of the very definite trade-off possibilities existing between efficiency, size/weight, regulation, frequencies, convenience, reliability, etc. Usually there is considerable difference between what it is possible to accomplish in the way of power conditioning in a given situation and what it is advantageous from the systems perspective to actually require. Somewhere a knowledgeable authority has to weigh the various compromises and make decisions which represent a reasonable balance between conveniences for individual subsystem designers and overall system requirements. Misuse of the capabilities afforded by power-conditioning developments is itself a potential problem area. For example, it is obviously unwise to acquiesce to a motor designer's request for sine-wave power rather than square-wave power in an instance wherein the only advantage to be gained would be a small reduction in motor heating and size if, as a result, the weight of an inverter and its filter had to be increased by an amount which cancelled the savings anticipated for the motor. Niceties such as state-of-the-art precision in voltage regulation and low-harmonic-content a-c outputs, though attractive from the viewpoints of individual subsystem designers, are not necessarily justified in an overall systems analysis.

Scant literature exists which focuses sufficient attention upon the overall systems considerations which are inherent in power conditioning work.[1,2]

Theoretical Considerations

The functions of inversion (changing direct current to alternating current), conversion (changing direct current derived at one voltage level to direct current available at another voltage level), and regulation (controlling the magnitudes of specific voltages and currents) are closely related from a theoretical viewpoint. Except in the special case wherein d-c to d-c conversion from a higher to a lower voltage is accomplished simply by dissipating energy across a dropping element, d-c to d-c conversion involves the function of inversion, in its broadest sense, as an intermediate step. Furthermore, the regulation of direct currents and voltages is a process which inherently requires either (a) a controllable reduction in voltage between the input and output of the regulator accomplished solely by a dissipation of energy, or (b) the introduction of an a-c component of voltage and current, i.e. the introduction of inversion, as an intermediate step in the regulation process.

Thus, generally speaking, the fundamental technological problems encountered in inversion, conversion, and regulation systems are the same. Certain basic principles dictate specific characteristics which must be a part of any such system if the system is to be physically realizable. For example, it may be proven that a system which does not have at least one active resistor (switching element) connected so as to form a series part of some simple closed circuit which contains a direct-current source of energy but no capacitors cannot cause any of the power provided by the direct-current source to be converted to power in the form of alternating currents and voltages.[3] Clearly, the role played by switching elements in power-conditioning technology is a permanent and vital one.

Present systems operated from direct-current energy sources generally depend on inductive phenomena as the basis of voltage step-up or non-dissipative voltage step-down. Such systems must be oscillatory in nature due to the finite flux and energy capacity of inductive elements. The necessary size of such elements for a given system will be dictated not only by the intrinsic capabilities per unit volume of the inductive element, but also by the maximum frequency, as determined by available switching elements or other limitations, at which the element may be operated. Other phenomena potentially useful for voltage conversion, such as piezoelectric effects or dielectric effects involving ferroelectrics, also must be used in oscillatory systems and also are subject, therefore, to the capabilities of available switching elements, if such systems are to be powered from d-c sources.[4]

To anyone working with the various concepts and approaches associated with the design of voltage converters and systems for inversion and regulation, certain additional truths make themselves felt. Often, although they consistently make themselves felt in the success or failure of various design concepts, these fundamental principles are recognized only in a semi-intuitive manner. Some formal study on a very fundamental level of the characteristics and intrinsic requirements of physically realizable conversion, inversion, and regulation systems would appear likely to be fruitful in the establishment of realistic long-term guidelines and goals for future component and system research in these areas.

Technological Trends

To date, the environmental requirements imposed on power-conditioning circuitry in spacecraft have been rather mild and well within existing capabilities. The primary design question has been "How can it be done best?" rather than "Can it be done adequately at all?" This situation, however, is beginning to change. Primary reasons for the change include:

1. The forthcoming needs for the use of considerably higher levels of power--Power requirements for space vehicles are expected to continue their rapid rate of increase, with power levels in excess of one megawatt not too unlikely within the next ten years. These requirements, including adequate protection systems, will have to be met with even more stringent reliability requirements than encountered today. It is desirable, therefore, that these requirements be met with solid-state power-conditioning systems.

2. The characteristics of the various new primary sources of electrical energy-- Thermionic generators, thermoelectric generators, nuclear thermoelectric generators, magnetohydrodynamic (MHD) generators, and fuel cells are very rapidly emerging from a primarily research and development phase into roles of practical importance in the generation of electric power. With each

such new power-generation system comes new power-conditioning problems. For example, efficient utilization of a one-volt, 1000-ampere direct-current output from a thermionic generator obviously poses problems, as does the utilization of a 1500-volt direct-current output of a MHD generator.

3. Environmental factors -- In accordance with the systems objectives, it is to be anticipated that the use of new energy sources will impose new environmental factors upon power conditioning systems. For example, it will probably be quite advantageous to be able to operate power-conditioning circuitry at a base-plate temperature of 150°C to 250°C as might be dictated by the temperature of the coolant for a nuclear reactor. Moreover, certain mission requirements also will strongly influence the operational environment of the power system. As an example, a spacecraft to explore the vicinity of a hot body, such as the sun, may require entirely new concepts of power conversion to enable operation at temperatures on the order of a thousand degrees centigrade. Temperature and radiation environments to be encountered as a result of the space vehicle mission or power generation system appear to offer severe challenges.

4. The effect of rapid changes in technical requirements upon power-system reliability -- Many of the switching elements and other components, which will have to be developed to make possible continued adequate power-conditioning capabilities, unavoidably will be very costly special-purpose devices which are manufactured in limited quantities. Typically, little economic stimuli, aside from that resulting from the specialized needs of space/military power conditioning, will exist to encourage the development, manufacture, and the generation of adequate reliability assurance for the more specialized of these elements. Further, the majority of these power conditioning systems are likely not only to employ newly developed components but also, as systems, to embody significant new design approaches. Clearly, the adequate specification and assurance of reliability will become an increasingly formidable problem. Timing, i.e. adequate long-range planning in correct anticipation of future requirements, is a key ingredient of the necessary reliability efforts.

Component Development

In the past, the capabilities of available solid-state switching elements have been the most limiting considerations in extending the capabilities of power conditioning equipment. In general, this situation continues today. Semiconductor rectification and switching elements, though they have undergone a continuing evolution in reliability, speed, degree of immunity to transients, useable temperature range, and power-handling capacity, are still the most limiting components in power conditioning circuits. However, it is encouraging to note the past and present rate of progress in the semiconductor-device area. And, for the first time, serious concern is being shown lest the capabilities of semiconductor devices overrun those of the magnetic and capacitive elements necessary for these circuits.

Semiconductor Elements, Active Devices. Progress in static-power-conditioning capability, for fundamental reasons referred to previously, has always been geared directly to progress in the development of more adequate static switching devices. When new or improved switching elements have been introduced, circuit development has usually been swift, such that at least some of the advantages offered by the new element are rapidly utilized. Often, in fact, the very rapidity with which newly available switching devices are integrated into power conditioning systems compromises reliability for the sake of the added efficiency, or power-handling capacity, or higher-frequency capabilities offered by the characteristics of the new switching-device development. The reliability compromise may be a result of poor system design by engineers not yet sufficiently sensitive to the vulnerabilities of an unfamiliar element, or may be a result of weakness inherent in the new switching element itself. An understandable temptation exists on the part of the system designer toward taking immediate advantage of significant system-performance improvements offered by a new element, with too little concern often being given to the meager reliability assurance which is so quickly available.

Though the semiconductor industry is little over ten years old, its technological progress has been such that, today, semiconductor devices are among the most reliable components used in electrical systems. Progress in the development of power-handling rectification and switching devices of ever greater power-controlling capabilities has been extremely rapid. However, the high voltages and currents and, particularly, the high-energy transients typically encountered in power-conditioning circuits have been and continue to be particularly formidable obstacles. Other challenges which are growing more acute include the development of devices for ever higher-temperature operation and for operation in a very high-radiation environment, such as might be encountered by an anti-missile missile or encountered in close proximity to a nuclear reactor.

Semiconductor rectifiers play roles in power-conditioning systems which are complementary to and as fundamental as the roles of the switching elements. However, semiconductor rectifiers have always been available with capabilities which significantly excel those of simultaneously available switching elements. Rectifier elements, involving only one p-n junction, are usually much simpler to fabricate than switching elements of comparable ratings. In addition, rectifier characteristics are such that unless its voltage ratings are exceeded, the device inherently always operates in a condition of low dissipation relative to the power it controls. Rectifiers are now available with controlled avalanche characteristics such that, even if their voltage-blocking ratings are briefly exceeded, the resulting transiently high dissipation within the device is well distributed over the rectifier junction and much less likely to be destructive to the device. Although isolated needs, e.g. the present need for a rectifier with a very low forward-conduction voltage drop to enable efficient usage in very low voltage circuits, will from time to time become particularly troublesome, it appears that rectifiers will continue to outpace switching elements in both electrical capabilities and environmental capabilities.

Presently available semiconductor switching elements may be conveniently grouped into two categories: (1) Those devices with continuously variable impedances, and (2) those devices with bistable voltage-current characteristics.

The primary examples of devices in the first category are power transistors. Other devices exist which rightfully belong in this category, such as photo-electric devices and Hall-effect or magneto-resistive elements. Certain of these other possible first-category device types have, in fact, been studied with the specific objective of evaluating their possibilities as power-switching elements, but, as yet, the transistor certainly has no serious challenger.[5,6]

Presently available bistable semiconductor switching elements include various devices using the basic PNPN structure of the controlled rectifier (controlled rectifiers, gate controlled switches, gateless anode-controlled PNPN switches), five-layer symmetrical switches, and tunnel diodes. To date, the PNPN-structured bistable devices, and particularly the controlled rectifier, have been the devices of primary interest in this category.

Though the transistor is a device whose impedance can be made to vary over a wide range, in power-conditioning circuits it is normally operated only in very high and very low impedance states and is switched between the very high and the very low impedance states as rapidly as possible. The speed at which this switching can be made to occur is one of the primary advantages of transistors as compared to other switching elements. As the result of the recent application of improved diffusion processes and other new manufacturing techniques it has been possible to reduce power-transistor switching intervals from times on the order of several microseconds to times on the order of tenths of a microsecond.[7,8] Such increased switching speeds have, of course, made practical much higher frequency operation of regulators and converters. As mentioned previously, frequencies (10 kc and above) are now becoming practical, from a switching-element viewpoint, which begin to strain the limitations of the other circuit components. And as will be mentioned again in a following section, such significantly increased frequency capabilities in transistors, and to a lesser extent in PNPN devices, brings into question the use of the traditional 400-cps frequency as a standard for the a-c portions of spacecraft electrical power systems.

Silicon transistors are now available, primarily on an experimental basis, with current ratings as high as 100 amperes, megacycle alpha cut-off frequencies, and saturation resistances as low as 0.001 ohm.[9] Commercial silicon power transistors are available with 500-volt ratings. The primary interest in germanium devices at present is in the low-voltage high-current range. Reasons for the rapid trend toward silicon devices have included, primarily, the higher temperature capabilities offered by these devices and the recent developments in device design and manufacturing technology which have allowed these capabilities to be realized. Apparently, some further extensions of the present upper temperature limitations of around 150°C for silicon devices will be possible through further refinement of internal-connection techniques and other mechanical problem areas. However, for operation at temperatures considerably above 150° to 200°C it appears necessary to look toward the use of other semiconductor materials with more suitable energy-band structures. Silicon carbide is an often-mentioned semiconductor with attractive high temperature possibilities.

Though there is a large region in which the capabilities of transistors and PNPN devices overlap, design trends have shown a pronounced preference toward using power transistors for those power conditioning applications well within their capabilities and using the various bistable PNPN switching devices for applications involving requirements which tend to exceed the voltage and/or current capabilities of transistors. Controlled rectifiers, for example, are presently available in voltage ratings of 1300 volts (IRC Type 70RE130) and current ratings of 470 amperes (GE Type GRW71H), although these ratings are not presently available in the same device. Among the difficulties which have discouraged more widespread use of these devices and often made transistors appear more attractive in situations where a choice exists are the following: (1) Transistors offer considerably faster switching speeds, (2) the complexity of the circuit techniques needed to control the turning on and, more particularly, the turning off of the PNPN devices, in general, exceeds that required for transistors, (3) because of the sensivivities of these PNPN devices to transients, i.e. the likelihood of accidental turn-on or failure to turn off due to transient voltages or overloads, special precautions must be observed in order to use these devices reliably in d-c circuits, and (4) a smaller number of circuit engineers have become highly competent in dealing with the technical problems involved in using these PNPN devices with their bistable, transient-sensitive, and highly nonlinear characteristics in d-c circuits than have become familiar with transistor design techniques.

Tunnel diodes have been used, along with special germanium transistors, as the power switches in very low-input-voltage converters.[10,11] However, notwithstanding such specialized applications, the voltage-current characteristics of tunnel diodes do not qualify these devices as very efficient or desirable inversion and conversion switching elements. The tunnel diode seems destined to play a possibly significant, but rather auxiliary type of role in the evolution of power-conditioning technology. Its most outstanding characteristic as a power-handling device is its extremely fast switching speed. This characteristic has been used, for example, to good advantage in combination with transistors to improve the transistor switching efficiency.[12]

Likewise, the impact of integrated-circuit technology upon the power-conditioning evolution will probably be somewhat limited. Thermal resistance considerations, i.e. the problem of adequate heat dissipation, inherent in high-power switching circuits considerably mitigate the size/weight advantages offered by integrated-circuit usage in other areas. Further, the primary cost and reliability advantages hoped for with the use of integrated circuits in other areas, e.g. data processing, largely disappear in view of the low-quantity, rapidly-evolving needs of space/military power-conditioning circuits. Peripheral areas, however, do exist within the spectrum of power-conditioning requirements wherein integrated circuits may make a substantial contribution to greater reliability. For example, the oscillators, counters, logic circuits, amplifiers, reference, error detection stages, etc. necessary to adapt power-conditioning systems to very precise system requirements, e.g. controlling the frequency of a power inverter from a quartz-crystal or other reference to within minute tolerances, may be considerable in number. Such low-power control circuits may lend themselves well to integrated circuit techniques.

With either PNPN switching elements or transistors, the power-conditioning-system designer is usually more concerned with catastrophic than degradation failures of the semiconductor elements. Very high-energy stresses are encountered by these switching elements both as a result of their normal power-controlling function and as a result of the possibility of accidental high-energy transients. The most common mode of transistor failure is the occurrence of collector-to-emitter short circuits caused by excessive dissipation within the device, often as a result of inductively-generated transients.[13] With PNPN devices, probably the most common mode of failure has been device burn-out as a result of accidentally turning on or failing to turn off the device in a direct-current circuit as a result of unsuspected voltage transients or momentary overloads. Thus, in the design of power-conditioning circuits more so than in many other electronic systems there is a requirement for a very high level of understanding and attention on the part of the designer to effects of thermal and electrical transient phenomena, margins of safety, etc. A growing depth of understanding and sophistication on the part of circuit designers and a growing number of persons highly qualified in this area is one of the more promising signs in the struggle for increased reliability.

Semiconductor elements, at present, are used as the rectification and switching devices for static power conditioning systems virtually to the exclusion of alternative types of elements. The reasons for this usage have been, of course, very valid. However, extrapolating present rates of development in semiconductor technology and comparing the results with certain specialized switching-device requirements which apparently are forthcoming leads one to the conclusion that switching elements of types other than semiconductor elements should be investigated. Two such specialized requirements have already been mentioned. They are the very high temperature requirements and the very high voltage requirements. The possibility of utilizing new semiconductor materials for high temperatures is an obvious possibility and has already been mentioned. Work is also being done on ceramic tubes which, although they apparently show little promise for low-voltage high-current circuitry, do however provide a way of switching and rectification at very high temperatures-above 500°C. For the area of very-high-input-voltage power conditioning, gas thyratrons of metal-ceramic construction are being developed and may well have future commercial as well as space/military power conditioning significance in conjunction with MHD sources.

The economic stimuli which have motivated the developmental efforts necessary to make available new transistors, controlled rectifiers, and other switching elements have reflected quite clearly and quite naturally an emphasis toward large-quantity markets. Highly specialized device requirements for power-conditioning applications as well as for others have often gone unsatisfied, not because they were technically unfeasible, but because the funding necessary for their development was not provided or because there was insufficient liaison between the circuit-minded engineer and the device-minded engineer to make the need known sufficiently far in advance. There is a need for considerably more coordination between these two groups of people - the people who put the switching elements to work and the people who design the elements themselves. A great many areas exist in which a more widespread mutual understanding by each group of the problems, alternatives, possible areas for trade off, etc. confronting the other group should facilitate overall progress.

As emphasized previously, the switching element is the nucleus of power conditioning systems. Switching device developments have, in general, set the pace for the overall rate of progress in power conditioning technology, not only in power-handling capabilities and size/weight but insofar as reliability is concerned. Symptoms of failed power conditioning equipment almost always have been or have included one or more failed semiconductor elements within the equipment. This has not been primarily a result of failures originating within the semiconductor elements themselves, but, more often, a consequence of the fact that the circuit functions performed by these elements make them targets for high energy-dissipation during electrical transients. Despite the existence of pressing needs in other component areas, it should be expected that progress in the area of switching elements will continue for some time to come to set the pace in the development of more adequate systems for power conditioning.

Passive Components. The same environmental extremes previously mentioned in relation to switching-element considerations will also require extensive developmental work on insulation systems, magnetic materials, inductors, transformers, and capacitors.

Considerable work has been and continues in progress on very-high-temperature insulation systems by wire manufacturers and the large electrical manufacturing companies. It appears now as if needs in this area will be adequately fulfilled. Work is also being directed toward specialized insulation requirements such as those exemplified by the temperature, high voltage, and unusual transient characteristics and requirements of ion-propulsion rocket power supply systems.[14] Although applicable materials and techniques for many of these newer problems will be found to be available, a great deal of effort will be required in the careful design and testing of these insulation systems in order to adequately assure reliability.

The rapid increase in the frequency capabilities of semiconductor switching elements is beginning to re-focus attention upon the need for improved magnetic materials. In the first half of the 1950's magnetic amplifiers were at their peak of popularity, and the spotlight was continually on magnetic-core materials with the attendant result that considerable effort by many groups of people was devoted to the development of materials with lower losses, greater squareness, higher saturation flux densities, less degradation with high temperatures, and improved radiation resistance. Since the coming of age of the transistor in the second half of the 1950's and more recently the advent of the controlled rectifier, these two devices have pretty much taken over the amplification requirements of government and industry. This resulted in a change of emphasis in magnetic materials research away from those directed toward improved characteristics for power applications to those areas where there existed greater interest and more pressing problems, such as thin magnetic films and ferrites for computer applications. A reawakening of interest and returning of attention to the problems of developing improved magnetic materials for the power-handling requirements of saturable and nonsaturating transformers and filter chokes to meet the specific requirements of high-frequency power-handling circuits for the space program is in order.

Capacitors are used in spacecraft power systems for filtering alternating current, for filtering direct current, and as energy storage devices for commutation, i.e. the turning off of controlled rectifiers in controlled-rectifier inverter circuits. The capacitor characteristics required for these three applications differ widely. However, a major problem in each application is the internal heating of the capacitors which is encountered as a result of the very high rms currents to which these capacitors are subjected in typical inverter and converter applications. Such internal heating is a particularly severe problem in commutating capacitors because of the extremely high rms currents which are characteristic of this application, and in d-c filter capacitors which are usually of electrolytic types which degrade rapidly with increasing temperature. From an environmental point of view, capacitors, and in particular electrolytic capacitors, are the most limiting passive components which are basic to power conditioning systems.[15]

Converters and Regulators

The number of alternative circuit types and variations of these types which have been developed for d-c to d-c conversion and regulation is quite large. The relative advantages and limitations of these circuits are quite varied. With some circuits, multiple isolated outputs are available; with others only a single output which shares a common potential with the input supply voltage is available. Some circuits are capable only of stepping up a direct voltage; others only of stepping down a direct voltage. Certain circuits, notably bridge configurations, better utilize existing switch capabilities in situations involving very high input voltages to the converter; other circuits, involving only one switching element in series with the input-voltage source, better utilize existing switch capabilities in low-input-voltage situations. In some circuits, all of the energy transferred from source to load is subjected to the switching and other processes normally associated with power conditioning; whereas in other circuits, often called "buck-boost" circuits only a relatively small fraction of the power delivered to the load is subjected to such processing.

A listing such as this could go on and on. To review the functional characteristics and compare in a meaningful fashion the merits of the innumerable individual circuits proposed and in use today would be a gigantic undertaking and would not contribute particularly toward accomplishing the objectives of this paper. Many specific circuits are described in the references listed at the end of this paper; many more are described elsewhere in widely available literature sources. Actually the very quantity per se of competitive circuit techniques, existing descriptions, performance claims and counterclaims, etc. is beginning to create a very significant problem. It is hoped that this discussion will help to focus enough attention on this problem that efforts may be encouraged which will mitigate its seriousness.

The problem referred to above is amply apparent in the fact that it is becoming increasingly more difficult for the circuit designer and, more particularly, for contracting and procurement people to realistically select between alternative approaches, to evaluate performance claims, to evaluate work proposals, and otherwise make valid comparisons. As a technology, power conditioning has certainly reached the point of maturity where steps should be taken promptly to establish meaningful and agreed upon figures of merit, to define standard tests and measurement procedures, and to recommend certain minimum data to be provided on all devices. Such a program might be undertaken by one of the professional societies such as IEEE to the mutual benefit of suppliers and the purchaser.

Converter and regulator circuits inherently employ numerous nonlinear elements and as a result are extremely difficult to analyze even with advanced analytical and experimental tools. Functional subtleties are repeatedly encountered which are quite important but which are extremely difficult to explain in the conventional concise manner of technical papers and reports. Often these finer details have simply been glossed over in circuit descriptions, leaving the uninitiated reader with a vastly oversimplified technical picture. It may be on such seemingly minor points as transformer winding techniques, diode recovery times, lead length, leakage inductance and stray capacitance, etc. that the reliability or satisfactory performance of the circuit hinges. Another problem in the same general area is the somewhat ambiguous manner in which circuit merits, efficiency, reliability, weight, etc. often have been described. Misleading emphasis has too often been given to the statement of isolated performance figures without adequate definition of exactly how these figures were obtained and without an adequate statement of other pertinent circuit data. For example, efficiency, frequency, weight, range of input voltage variation through which regulation is sustained, reliability, and certain other factors generally may be traded one for the other. A mere statement of efficiency obviously provides no real figure of merit for the system. Such piecemeal information, based on unknown measurement procedures, can be seriously misleading and therefore costly and delaying to designers and to contractors.

Until reasonable and adequate standards in this area can be formulated and adopted, both the supplier and the purchaser are handicapped. One supplier cannot affort to claim less for his approach than is claimed for a competitive approach. And in the absence of an adequate set of ground rules, many shifts in emphasis, tacit omissions, etc. by the proponent of a given system are possible which, though, not incorrect, can certainly be very misleading. On the other hand, the burden of writing realistic specifications which is placed on the purchaser also is vastly greater in the absence of adequate previously agreed upon standards.

Inverters

Rates of progress in the areas of d-c to d-c conversion and d-c to a-c inversion have generally been governed by the same technical obstacles, and progress in these two areas has been about equal in most aspects. There have been some notable areas of contrast, however. Generally, inverters, especially those for three-phase systems have involved considerably more complexity that d-c to d-c converters of similar power ratings. Also, it has usually been the case that an inverter of a given power rating would be expected to weigh considerably more than a d-c to d-c converter of the same rating. The previously mentioned needs for standard test and evaluation criteria exist throughout the spectrum of power-conditioning equipment and will not be re-emphasized in connection with inverters.

The most common load for inverters, i.e. the most compelling need for a-c power in spacecraft and launch vehicles has been motors (pump motors, gyro motors, recorder motors, etc.). The use of alternating-current power can be advantageous in a number of ways: For example, it can avoid the necessity for the commutation and brushes which are generally found in d-c motors and which are highly undesirable for use in space vehicles, and it can provide precise means of determining the speed of a motor.

It is interesting to note, however, in connection with the mention of brushes in d-c motors that considerable work has been done and is currently in progress on the development of brushless d-c motors. These machines use solid-state switching techniques to perform the switching functions which in conventional d-c motors are performed by the brushes and commutator. It can be proven that one or more switching elements are necessary in order to operate any motor from a direct current source.[3] However, significant advantages in weight, size, and complexity can result by making the necessary switching an integral part of the motor and its mode of operation, rather than incorporating the switching in an external inverter and providing alternating current to an a-c motor. In reality, however, these so-called brushless d-c motors are simply a specialized application of power conditioning techniques, and the power capabilities, environmental capabilities, etc. of these motors at least so far as the non-mechanical aspects of the units are concerned will go hand in hand with technological progress in the power-conditioning field in general.

Since with d-c to d-c converters the output is a direct voltage, the intermediate switching frequencies employed are of little consequence, except as they relate to the size/weight and efficiency of the converter. Consequently, as switching elements of ever greater switching speeds have been made available, the frequencies used in d-c to d-c converters have progressed steadily upward. A steady reduction in the size and weight of the transformers and the inductive and capacitive energy storage elements used in d-c to d-c converters has resulted.

Inverters are generally required to supply a-c power to a load at a predetermined frequency. Typically, this frequency has been 400 cycles per second (cps). In contrast to the d-c to d-c converter case in which gradual improvements in switching-element speed made possible a gradual but steady increase in frequency and decrease in size and weight, it has remained more practical to continue to perform the switching in 400-cps inverters at the 400-cps frequency. Thus, the size/weight reduction in d-c to d-c converters made possible by faster switching elements has not been paralleled by similar reductions in inverters. At the present time, however, it seems apparent that this situation has definitely started to change for the better.

In systems requiring a sine-wave output, significant size and weight savings are now being obtained through the use of multiple stages and waveshape-addition techniques in order to generate a waveshape which closely approximates a sine wave and requires very little filtering.[2,16-18] These techniques involve considerable complexity and result only in savings in filter size and weight rather than in savings in the inverter transformer weight. But in earlier inverters, the filter stage has often outweighed the actual inverter stage.

In addition, it is significant to note that switching-device improvements have now reached the point at which switching frequencies which are more than an order of magnitude greater than 400 cps are practical even at high power levels. With this recent availability of such fast switching elements, it has become practical for the first time to consider systems in which the switching frequency is very high in relation to the output-voltage frequency and in which the desired low-frequency output waveform is approximated by modulating the high frequency waveform.[19,20] By using these techniques, for example, in a transformerless bridge inverter, it is possible to generate a low-frequency sine wave, e.g. 400 cps, with a circuit in which the size and weight of all magnetic and capacitive components are dictated by the very high switching frequency rather than the low frequency output. Such transformerless inverters need to be supplied with direct voltage whose value is at least $\sqrt{2}$ times the desired sinusoidal a-c output voltage. Usually this will require a d-c to d-c converter, thus adding to the system complexity and adversely affecting efficiency. It is also possible to accomplish the desired voltage conversion with a high-frequency d-c to a-c inverter and then to perform appropriate switching upon this high frequency a-c in order to generate the desired low frequency waveform. Providing necessary reactive current paths under all circuit conditions and eliminating circuit transients are major considerations in these circuits. Despite this, such techniques will probably begin to play a significant role in the meeting of future requirements for low-frequency (low compared to state-of-the-art power-conditioning frequency capabilities) a-c power in space.

Questions concerning the desirability of continued emphasis on 400 cycles per second as a standard frequency for space vehicle electrical equipment are beginning to be asked more and more frequently. Certainly power-conditioning limitations are no obstacle toward the use of a considerably higher frequency than 400 cps, and if a choice were to be made strictly from a power-conditioning viewpoint (frequency/weight vs. efficiency considerations) a frequency would undoubtedly be chosen which would be too high to be practical as a standard in view of other considerations. For example, distribution problems in the form of line reactances may become a problem at frequencies in the kilocycle range. It is also somewhat difficult to design low-speed a-c motors for operation from very high-frequency alternating current.

Apparently the majority of the electric power to be used in space vehicles will continue to be derived from direct-current sources. It appears likely that d-c distribution systems may be used extensively. For these and other reasons, such as the critical importance of size, weight, and efficiency, past precedents in the form of ship-board electrical systems, aircraft electrical systems and land-based generation and distribution systems provide few or no guidelines for the power-conditioning and distribution-system planning for the electrical power needs of future spacecraft, manned lunar stations, etc. Vital questions will need to be answered, of which the choices of a standard power frequency and standard d-c and a-c voltage levels are only one aspect. However, such decisions must be a result of the evolvment of energy-source characteristics and capabilities and of the rapidly changing nature of equipment loads, power levels, etc. These characteristics and requirements are now in such a state of flux as to discourage attempts at the present to make long-term decisions on these matters.

Summary and Conclusions

Preceeding sections of this report pointed out and briefly discussed a number of factors which are particularly important aspects of the evolving technology of power conditioning for spacecraft electrical systems. In so doing, an attempt was made to focus attention primarily on basic considerations of long-term significance and to avoid, insofar as possible, discussion of numerous detailed problems which appear to be of a more transitory nature.

What follows is a concise summary of certain of the conclusions drawn from the earlier more detailed discussions. These conclusions are based on the background presented earlier and their proper interpretation may be difficult if this background material is not borne in mind.

1. The switching element is presently and will continue for some time to be the single most limiting component of inversion and conversion systems.

2. Confidence in the ability of power conditioning equipment to perform reliably in operational situations is still lacking. Actual performance records are considerably poorer than would be expected from consideration of the environmental requirements and of the potential reliability of the component devices themselves. A great deal of the burden of assuring reliable performance in these high-power transient-prone circuits rests upon the circuit designer and his knowledge and skill.

3. A certain amount of fundamental research directed toward establishing theoretical criteria for physically realizable conversion, inversion and regulation systems should prove fruitful in helping to establish realistic long-range guidelines and goals for future component and system development projects. The objectives of such a basic research program as proposed here would be entirely different from those goals which motivate the design-oriented analyses of existing systems.

4. Almost all of the basic components used in power-conditioning circuits will be hard pressed by some of the environmental requirements which apparently will be encountered in future systems, notably high temperature and large radiation dosages. Semiconductor elements and electrolytic capacitors are presenting the earliest obstacles. Often it may be desirable to physically locate power-conditioning

equipment very close, for example, to a nuclear power source or to a thermionic or thermoelectric generator. For such reasons, the environmental requirements to be met by power-conditioning equipment often may be considerably more stringent than those imposed on the other electronic equipment necessary to the mission.

5. The inevitably continuing increase in power requirements for spacecraft will be a vital factor in determining the trends of developments in the power-conditioning area.

6. Although peripheral needs within the spectrum of power-conditioning requirements, for example, counters, drive circuits, low-level amplifiers, etc. are well suited to the use of integrated circuit techniques, the overall significance of integrated-circuit technology in this area would appear to be considerably more limited than in other areas of application.

7. The specification of 400-cps sinusoidal sources for applications where a-c power is required clearly does not take fullest advantage of present inverter capabilities. To finalize on one or more frequencies or on specific d-c and a-c voltage levels for use as long-term standards in the space program seems premature at the moment, but definite steps to establish these when it does become practical to do so should be initiated.

8. As a technology, power conditioning has reached the point of maturity where steps should be taken promptly to establish meaningful and agreed upon figures of merit for power-conditioning equipment, and to define standard tests and measurement procedures.

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